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RESEARCH ARTICLE

Learning to read upside-down: a study of perceptual expertise and its acquisition

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Abstract Reading is an expert visual and ocular motor function, learned mainly in a single orientation. Characterizing the features of this expertise can be accomplished by contrasts between reading of normal and inverted text, in which perceptual but not linguistic factors are altered. Our goal was to examine this inversion effect in healthy subjects reading text, to derive behavioral and ocular motor markers of perceptual expertise in reading, and to study these parameters before and after training with inverted reading. Seven subjects engaged in a 10-week program of 30 half-hour sessions of reading inverted text. Before and after training, we assessed reading of upright and inverted single words for response time and word-length effects, as well as reading of paragraphs for time required, accuracy, and ocular motor parameters. Before training, inverted reading was characterized by long reading times and large word-length effects, with eye movements showing more and longer fixations, more and smaller forward saccades, and more regressive saccades. Training partially reversed many of these effects in single word and text reading, with the best gains occurring in reading aloud time and proportion of regressive saccades and the least change in forward saccade amplitude. We conclude that reading speed and ocular motor parameters can serve as markers of perceptual expertise during reading and that training with inverted text over 10 weeks results in significant gains of reading expertise in this unfamiliar orientation. This approach may be useful in the rehabilitation of patients with hemianopic dyslexia.

Keywords Word · Expertise · Perceptual learning · Rehabilitation · Hemianopic dyslexia

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Introduction

Reading is a complex skill that involves an intricate interplay between visual perception and ocular motor function. It has both parallel and serial components. It is serial in that sentences and paragraphs are read with a series of fixations linked by small saccades that span 6–9 letters on average, as the subject's point of current fixation moves across the line from left to right in western cultures, with a long return saccade from the end of one line to the beginning of the next (Rayner 1998). During each fixation, perceptual information is acquired and processed in parallel, not only from the point of fixation but also from an asymmetric horizontal region surrounding it. In cultures that write from left to right, this 'visual span' (letters that can be identified in one fixation) extends from about three letters left to seven letters right of fixation, while the 'perceptual span' (number of letters from which useful information can be extracted) ranges from 3–4 letters left to 15 letters right (Rayner and McConkie 1976). Fixations are very brief, lasting 200–250 ms on average, sometimes as short as 50 ms, indicating that written text is processed rapidly and efficiently, due to a significant perceptual expertise that literate subjects have acquired over years of experience.

What are the characteristic features of this expert visuomotor function? As reading is a skill that is acquired and practiced by literate subjects nearly exclusively in a single orientation, namely upright, its efficiency shows a dependence on orientation (Aulhorn 1948; Kolers 1968; Kolers and Perkins 1975). By way of analogy, in the field of face perception, studies claim that inversion is more detrimental to face recognition than it is to recognition of generic objects (Yin 1969; Valentine 1988). This 'face inversion effect' is attributed to years of predominantly upright experience in acquiring face expertise. Considering the years spent reading by the typical literate person, one might expect a similar inversion effect for words, but this has been far less studied than face inversion effects. Nevertheless, there are some reports to support a similar 'word-inversion effect.' One study using a same/different task found a larger inversion effect for Chinese characters than for pseudo-characters (Kao et al. 2010). Paralleling the Thatcher illusion for faces, in which rotations of the eyes and mouth are not perceived when the face is inverted (Thompson 1980), an alteration caused by mirror reflection of letters is easily detected in upright but not inverted words (Parks 1983). In a study of how whole faces or words modulate the recognition of facial features or letters, inversion effects were similar for both (Martelli et al. 2005). Other studies document that it takes longer to read passages of text when they are inverted (Kolers 1968).

However, there is no detailed information on how inversion specifically affects the characteristics of fixations and saccades made during the reading of extended sections of text. Studying the upright/inverted contrast in such ocular motor behavior can reveal important signature effects of reading expertise. An alternate approach to determining expertise effects is to study subjects as they learn to read, usually children (Taylor 1965; Lefton et al. 1979; Rayner 1985). In general, such studies show decreases in fixation duration, the number of fixations, and the proportion of saccades that are regressive (moving from right to left), and an increase in saccade amplitude as children develops reading proficiency, but this approach confounds the acquisition of perceptual with linguistic competence. In contrast, because inversion alters only the perceptual and not the linguistic properties of text, a comparison between upright and inverted reading in adult readers can isolate the effects of perceptual expertise alone. How quickly this perceptual expertise can be acquired through training is an equally interesting question and relevant to the fields of both perceptual learning and neuro-rehabilitation.

The goal of this study was to examine in more detail the process of inverted reading in healthy subjects. There were two main aims. First, we aimed to characterize the effects of perceptual expertise in behavioral and ocular motor parameters during reading: We hypothesized that the contrast between upright and inverted reading would provide a valuable index of this expertise. Second, we aimed to determine the changes that could be generated by repeated practice with inverted reading over a defined period. Thus, we trained subjects to read inverted text over 10 weeks and contrasted pre- and post-training evaluations of inverted reading in our subjects.

Methods

Subjects

Eight subjects were initially recruited, but one dropped out after completing only 3 of 30 training sessions, and her data will not be considered further. Therefore, the analyzed subject group (Table 1) consisted of seven healthy subjects (four males and three females) with a mean age of 34.9 years (S.D. 13.2). All were right-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield 1971). They were recruited through the volunteer section of Craigslist and paid $10 per hour. All had normal corrected vision, English as first language and no report of reading problems. The institutional review boards of Vancouver General Hospital and the University of British Columbia

Table 1 Subject information

Subject	Gender	Age (years)	Edinburgh handedness	Aloud			Silent		
				Upright	Inverted		Upright	Inverted	
				Pre	Pre	Post	Pre	Pre	Post
				Reading speed (words/min)					
ANS	F	55	85+	200	73	134	389	91	137
DEB	F	40	100+	185	52	137	346	51	134
JOG	M	22	80+	193	125	202	270	117	231
MIK	F	23	100+	159	127	201	251	161	178
NIM	M	28	100+	192	58	161	291	76	153
STF	M	49	85+	163	118	167	337	139	159
PHR	M	27	45+	189	158	199	352	189	239

approved the protocol, all subjects gave written informed consent, and the experiment was conducted in accordance with the principles of the Declaration of Helsinki.

Apparatus and stimuli

For pre- and post-training assessments, subjects were seated before a 21-inch monitor with a screen resolution of 1,024 × 768 pixels. A LabTec C-315 microphone was used for audio recordings. A head rest and a chin rest were used to stabilize the head. Eye movements were recorded from the left eye with an Eyelink 1000 video eye-tracker (www.sr-research.com). For the study of single-word reading, subjects were seated 57 cm away from the screen, so that 1 cm on the screen corresponded to 1° of visual angle. For the study of paragraph reading, subjects were seated 37 cm away.

Pre- and post-training assessments

Single-word reading

The stimuli consisted of four lists of 70 words, 10 each for 7 different word lengths ranging from 3 to 9 letters. The words were obtained from the MRC psycholinguistics database (http://www.psych.rl.ac.uk/MRC_Psych_Db.html) (Coltheart 1981) and were matched for written Kucera-Francis frequency: The mean frequency of the words was 62.4 (s.d. 53, range 16–258) occurrences per million words encountered. The experiment was presented with Experiment Builder 1.10.165 (www.sr-research.com).

In the pre-training assessment subjects saw two lists, one upright and one inverted. After training, they saw the remaining two lists, again one upright and one inverted. The order of the lists was counterbalanced, so that each list appeared in the pre-training assessment for half of the subjects and in the post-training assessment for the other half. Likewise, each list appeared upright for half of the subjects and inverted for the other half.

Upright and inverted lists were presented in separate blocks of 70 trials each. Each block was preceded by a practice trial of three words in the orientation for that block. The words were saved as graphic files with Adobe Photoshop CS 8.0 (www.adobe.com) and displayed in black on the center of a white screen, in 56 pt. Courier New font, in which each letter occupies a similar spatial extent, in our case 1° of visual angle per letter.

Each trial started with a fixation cross of 0.7° width that was replaced after 2,000 ms by a word. The subject's task was to read the word aloud. A microphone captured the subject's vocal response: The interval between onset of the word and the onset of their verbal reply was considered the response time. The audio recordings of all responses were reviewed to ensure that the marker for latency was triggered as the word was read. The trial was excluded if the subject read the word incorrectly, if the response was not triggered, or if it was triggered by sounds such as coughing or non-verbal noises.

The 70 words were randomly ordered within each block. Half of the subjects began with upright blocks, while the other half began with inverted blocks, and the same order was used for pre- and post-assessments for each subject.

Paragraph reading

Eye movements were first calibrated by having subjects fixate on 9 points arranged in a grid (screen center and halfway to screen edges in vertical and horizontal directions), which was then validated to an accuracy of less than 1.0° of error. Before each trial of paragraph reading, the screen displayed a cross at center, which subjects had to fixate with a position error of less than 1.0° for 200 ms, for the trial to start. If not, a black dot appeared at the center and calibration was repeated.

Stimuli were eight standardized paragraphs from the International Reading Speed Test or 'IReST' (Trauzettel-Klosinski and Dietz 2012), which had been entered and saved as graphic files with Adobe Photoshop CS 8.0. These paragraphs are graded for difficulty from A to C, with A being the easiest. The texts were displayed in 12-point Verdana font, which at the viewing distance of 37 cm presented about 3 letters per degree of visual angle. Programming of the experiment was done in Experiment Builder 1.10.165 (www.sr-research.com).

There were four different paragraph reading conditions. One set was read aloud and verbal responses recorded for analysis of accuracy, while a second set was read silently with eye movements recorded. In each set, there was one paragraph read upright and one paragraph read inverted. Subjects were instructed to read for comprehension and to press a button on a keypad when they were finished.

The paragraphs were paired according to their difficulty level so that the same subject read different paragraphs with a similar level of difficulty for pre- and post-assessments. They were counterbalanced so that each was read in the pre-training assessment by half of the subjects and in the post-training assessment by the other half. Similarly, each was read upright by half of the subjects and inverted by the other half. Half of the subjects began with upright blocks, while the other half began with inverted blocks, and the same order was used for pre- and post-assessments for each subject.

Training procedure

The training consisted of reading novels upside-down online. The subjects were instructed to read three times a week for 30 min per session for 10 weeks, giving a total of 30 training sessions. They were instructed to do the training between 1800 h and 2000 h and to spread out the sessions through the week. The participants got an email reminder every week.

Subjects chose from a list of novels that were rated at an eighth-grade comprehension level or easier, as assessed with the Flesch Reading Ease and the Flesch–Kincaid Grade Level. If they finished a novel, they were given a new one with the same level of difficulty. These were Alice in Wonderland by Lewis Carroll, The Count of Monte Cristo by Alexandre Dumas, and The Scarlet Pimpernel by Emmuska Orczy. Each subject chose a book that they had not read before. The text was displayed on the screen in 12-point Verdana font. The text was entered manually and then inverted as a block with in-house software. Thus, the page of text began at the lower right of the screen and ended at the upper left.

The subjects were able to pause the session if necessary. The time they spent on each page was collected and used to calculate average reading speed per session. We reinforced reading for comprehension by testing subjects with multiple choice questions about the content and plot after every fifth page.

Analysis

Progress through training was assessed for each subject with a linear regression of the reading speed of each session against session number.

For pre- and post-training single-word reading, we tabulated the frequency of errors, which was the number of incorrect responses divided by the number of valid trials. We then calculated the mean response latencies for all valid correct trials within each block of 70 trials. We also calculated the slope of the relationship of mean response latency as a function of word length within each block, which corresponds to the word-length effect. This index assesses how efficiently words are processed as whole objects: In healthy subjects reading upright text, the word-length effect is minimal, whereas it is increased in subjects with either low-level visual problems such as hemianopia or high-level encoding problems such as pure alexia (Leff et al. 2006; Sheldon et al. 2012).

From paragraph reading, we calculated the reading speed for both reading aloud and reading silently. For reading aloud, we calculated error frequency, as the number of words read incorrectly and not self-corrected divided by the number of words in the paragraph. For silent reading, we obtained ocular motor measures. While some reading studies perform detailed analyses of word-based parameters such as the probability of skipping, refixations within a word, the duration of fixations on a word, and the total reading time per word (Laubrock et al. 2006), we focused on broader paragraph-based parameters to provide a global picture of reading efficiency. Thus, we examined the total number of fixations, mean fixation duration, number of forward saccades, and number of regressive saccades made during reading of a paragraph. For regressive saccades, we did not include primary or secondary return saccades to the beginning of the next line.

Our first analysis focused on characterizing reading expertise by contrasting upright with inverted performance from the pre-training assessment session. This used *t* tests with Bonferroni correction for multiple comparisons, adjusted for inter-item correlation. Our second analysis focused on characterizing the gains made from training by contrasting pre- and post-training performance for inverted text. Again, this used *t* tests with Bonferroni correction for multiple comparisons, adjusted for inter-item correlation (Sankoh et al. 1997). As an additional illustrative analysis, we also computed an 'expertise acquisition index' for each parameter. This followed the rationale that an increase in expertise with inverted text should reduce the difference between upright and inverted text performance after training. Hence, we divided the difference between upright and inverted text after training by the difference between upright and inverted text before training and subtracted this value from 1 to give the degree of expertise acquired through 30 sessions of training.

Results

Training progression

All but one subject (MIK) showed highly significant improvements in reading speed through the 30 sessions (Fig. 1). The mean slope of the regression was 1.17 words/min per session (s.d. 1.36): of the six who improved, the slopes ranged from 0.72 to 3.00 words/min per session. Thus, over the entire 30 sessions, subjects gained on average 35 words/min, with a range of 22–70 words/min in the six who improved (MIK showed a net gain of only 0.73 words/min).

Expertise effects: upright and inverted contrasts before training

For single words, mean reading latency was over twice as long for inverted words, 1,190 versus 517 ms for upright words [$t(6) = 4.61$, $p < .0037$], and there was a larger word-length effect for inverted words, 158 ms/letter as opposed to a mere 5 ms/letter for upright words [$t(6) = 3.60$, $p < .012$] (Fig. 2). Subjects were slower at reading inverted paragraphs either silently [$t(6) = 7.07$, $p < .0004$] or aloud

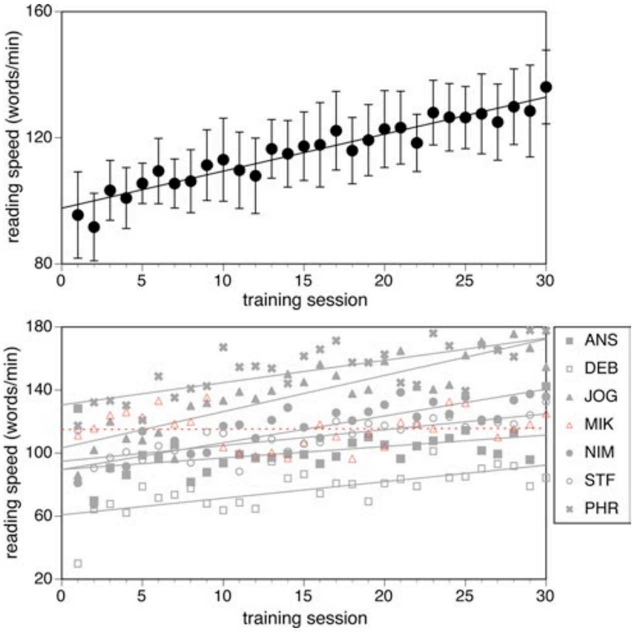

Fig. 1 Training progression. *Top graph* shows group mean, with *error bars* corresponding to one standard error and the *solid line* showing the fitted linear regression. *Bottom graph* shows the data for each individual subject. MIK (*dotted line* and *hollow triangle symbols*) is the subject who did not show improvement in training progression

[$t(6) = 4.48$, $p < .0043$] (Table 1; Fig. 3). Accuracies for both single words and paragraphs were high, with subjects reading 100 % of upright and 97 % of inverted words correctly, and 100 % of upright and 99 % of inverted paragraph text correctly.

Ocular motor parameters (Figs. 4, 5) showed that compared to their performance with upright text, subjects reading inverted paragraphs used more fixations [$t(6) = 4.16$, $p < .006$] and these fixations had longer durations [$t(6) = 4.17$, $p < .006$] (Fig. 6). They made more forward saccades [$t(6) = 5.18$, $p < .002$] (Fig. 7). While they made on average 11 (s.e. 4.4) regressive saccades for an upright paragraph, corresponding to 10 % (s.e. 3.5) of all saccades, with inverted text they made far more regressive saccades [mean 55, s.e. 18, $t(6) = 2.59$, $p < .041$], corresponding to 18.6 % (s.e. 3.9) of all saccades. The amplitudes of forward saccades were smaller for inverted reading [$t(6) = 6.95$, $p < .0004$], but there was no difference in the amplitude of regressive saccades [$t(6) = 0.55$, $p = .60$].

Effects of training on inverted reading

Reading latencies for single inverted words were faster after training [$t(6) = 3.19$, $p < .012$], and there was a trend to a reduction in the slope of the word-length effect, from

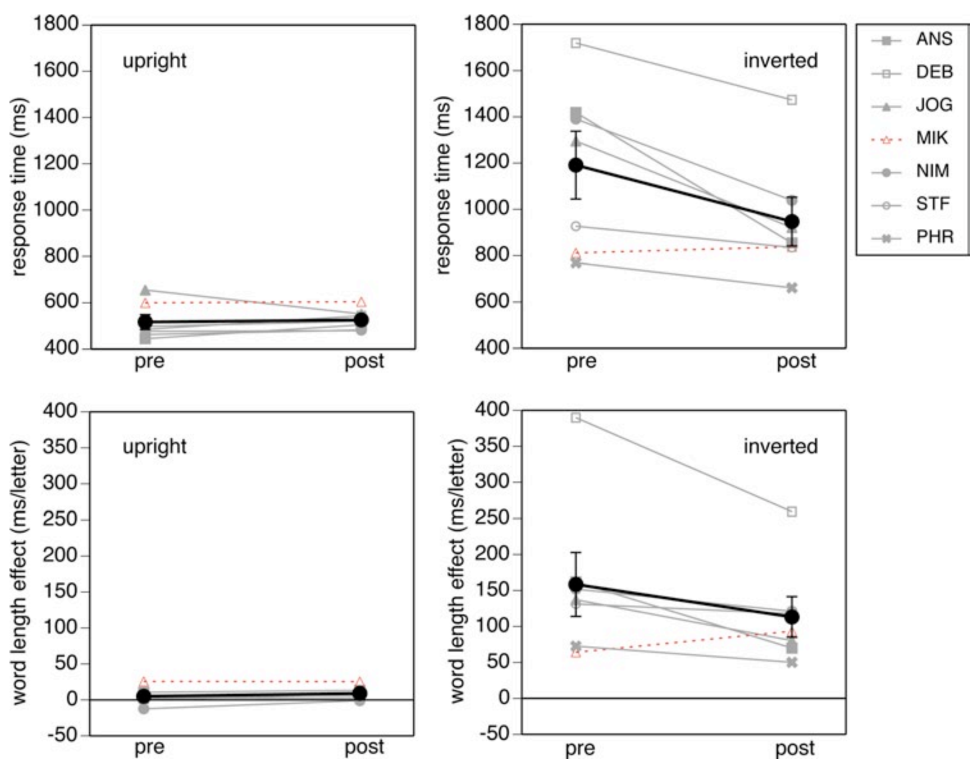

Fig. 2 Single-word reading. *Top graphs* show response time. *Bottom graphs* show the word-length effect. *Left graphs* show performance with upright text, and *right graphs* show performance with inverted text. Data for both individual subjects (*gray lines* and *symbols*) and the group mean (*thick black line* and *disk symbol*, with *error bars* showing one standard error) are shown. MIK (*dotted line* and *hollow triangle symbols*) is the subject who did not show improvement in training progression

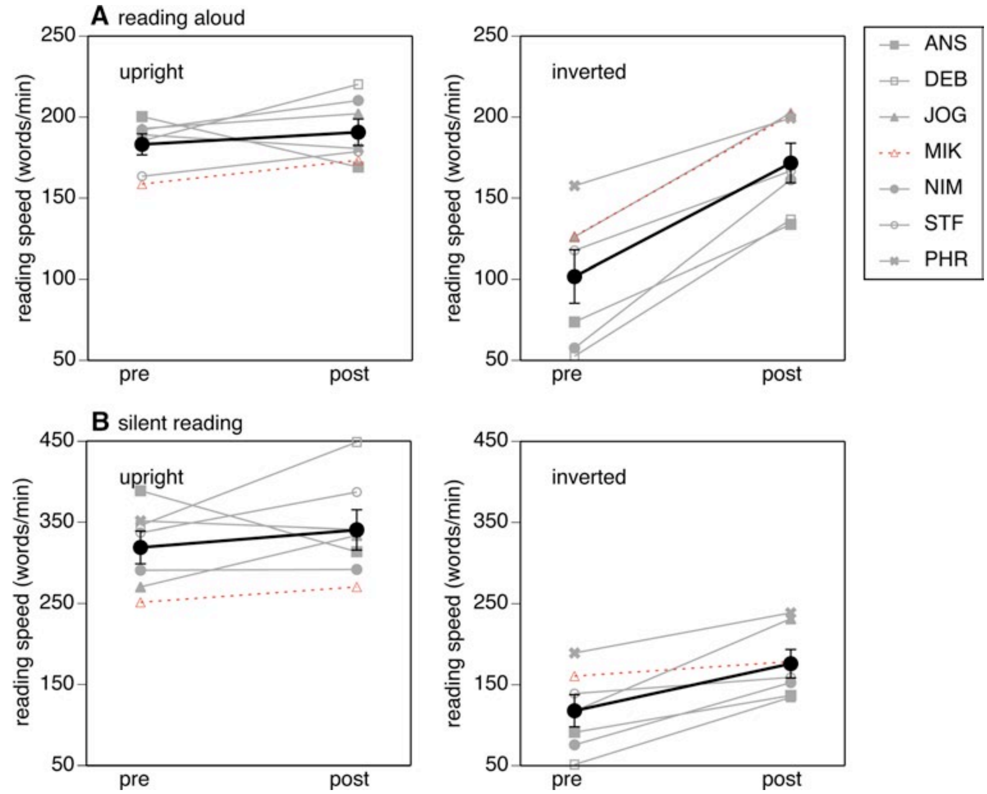

Fig. 3 Paragraph reading. **a** *Top graphs* show reading aloud. **b** *Bottom graphs* show reading silently. *Left graphs* show performance with upright text, and *right graphs* show performance with inverted text. Data for both individual subjects (*gray lines* and *symbols*) and the group mean (*thick black line* and *disk symbol*, with *error bars* showing one standard error) are shown. MIK (*dotted line* and *hollow triangle symbols*) is the subject who did not show improvement in training progression

a mean of 158 ms/letter before to 113 ms/letter after training [$t(6) = 2.26$, $p < .065$] (Fig. 2). Expressed as indices of expertise acquisition, there was a 37 % expertise gain for single-word reading latency and 32 % for word-length effect. Inverted paragraph reading speed (Table 1; Fig. 3) was faster after training for both reading silently [$t(6) = 4.38$, $p < .0047$] and reading aloud ($t(6) = 8.68$, $p < .0001$), corresponding to mean expertise gains of 18 % for silent reading and 77 % for reading aloud. Accuracies were high for inverted reading both before and after training, with subjects reading 97 % of pre-training and 99 % of post-training words correctly and 99 % of pre-training and 100 % of post-training paragraph text correctly. For upright text, training on inverted reading did not change the latencies or accuracy of single-word or paragraph reading.

Eye movement parameters showed that after training subjects used less fixations during paragraph reading [$t(6) = 2.75$, $p < .034$] and there was a trend to shorter duration of fixations [$t(6) = 2.36$, $p < .056$] (Fig. 6). These corresponded to expertise gains of 53 and 32 %, respectively. There was also a trend after training to fewer forward saccades [$t(6) = 2.54$, $p < .044$], an expertise gain of 38 %, and a trend to fewer regressive saccades [$t(6) = 2.34$, $p < .058$], an expertise gain of 80 % (Fig. 7). Looking at regressive saccades as a percentage of all saccades, there was a reduction from 18.6 % (s.e. 3.9) before training to 9.7 % (s.e. 1.5) after training [$t(6) = 3.10$, $p < .022$]. The amplitude of forward and regressive saccades did not change, however (Fig. 8). Again, there were no changes in any ocular motor parameter for upright reading.

Relation of upright reading efficiency to training effects

We also examined whether upright reading efficiency predicted an individual's ability to read inverted text. Before training, there was no relationship in silent reading speed between upright and inverted text [$r = 0.18$, $F(1,6) = 0.21$, $p = 0.66$]. The gain in inverted silent reading speed between the pre- and post-training assessments also did not correlate with initial upright silent reading speed [$r = 0.17$, $F(1,6) = 0.16$, $p = 0.70$]. However, when we excluded subject MIK, the anomalous subject who did not show any progression over training, there was a trend to a relationship [$r = 0.68$, $F(1,5) = 4.41$, $p = 0.089$]. When we examined the slopes of the regression indicating the rate of gain in reading speed over the 30 sessions of training, there was no relationship with MIK included [$r = 0.10$, $F(1,6) = 0.06$, $p = 0.81$], but a highly significant one with MIK excluded [$r = 0.92$, $F(1,5) = 26.9$, $p < .003$]. Thus, although the number of subjects is small, there is a suggestion that more efficient readers may show greater and more rapid gains in inverted reading speed.

Fig. 4 Example of fixations in subject JOG. The text read is printed with fixations superimposed as *gray disks*. The diameter of the disk is proportional to the duration of the fixation. *Top graphs* show pre-training reading fixations, *bottom graphs* show post-training results

Discussion

Our contrasts between upright and inverted reading in the pre-training assessment shows that perceptual expertise for reading is characterized by very rapid reading of single words and paragraphs both aloud and silently and minimal word-length effect for single words. The ocular motor signature of perceptually expert reading is the use of a small number of very brief fixations with fewer and larger forward saccades and fewer regressive saccades. Ten weeks of 30 sessions of training on reading inverted text improved many of these parameters in inverted text reading and reduce the difference between upright and inverted text, indicating the development of partial expertise for inverted reading. A reasonable estimate of expertise gain appears to be about 30 % for most parameters, with some such as the number of regressive saccades and speed for reading aloud showing even more impressive gains, and some notable exceptions such as forward saccade amplitude that show no change. Evaluation of performance during training suggested that subjects' inverted reading speed gained about 1.2 words/min for each 30-min session or 35 words/min for the entire 10 weeks of training.

Contrasts in performance between upright and inverted text essentially reveal the contribution of perceptual expertise to the reading process. As others have noted (Kolers 1975), this transform does not alter linguistic properties of the text, such as the spelling and morphemic construction of words and the syntactical structure of passages: Hence, any difference in reading reflects the impact of familiarity for and experience with the perceptual form. Since reading is practiced nearly exclusively in the upright orientation, its efficiency shows a dependence on orientation (Aulhorn 1948; Kolers 1968; Kolers and Perkins 1975), just as faces do for the same reason in the face inversion effect (Yin 1969; Valentine 1988). We found that, before training, silent reading speed for inverted text was three times slower than that for upright text, which is very similar to the finding of a prior study (Kolers 1968), though not as large as the eight-fold difference found in another (Kolers 1975).

Our study reveals how this orientation-dependent perceptual expertise with reading is manifest in the eye

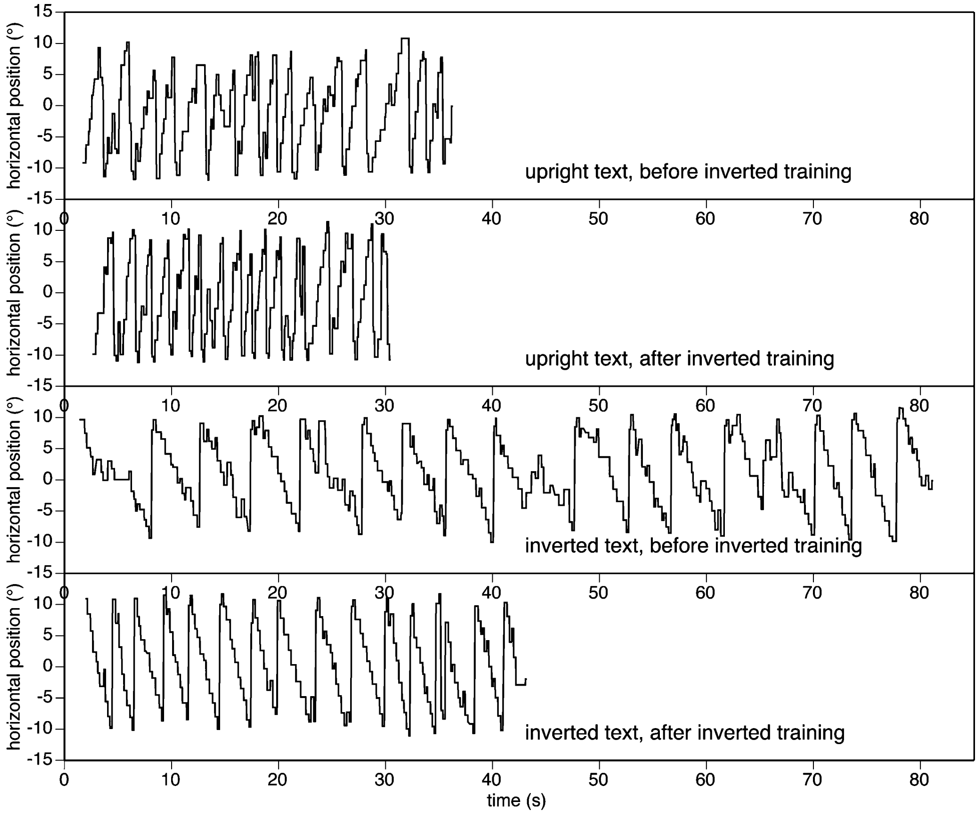

Fig. 5 Example of reading eye movements in subject JOG, in the pre- and post-training assessments. Horizontal eye position is plotted against time in all four plots; positive values are right of screen center, and negative values left. *Top graph* shows reading of upright text before training, *second graph* shows reading of upright text after training, *third graph* shows reading of inverted text before training, and *bottom graph* shows reading of inverted text after training

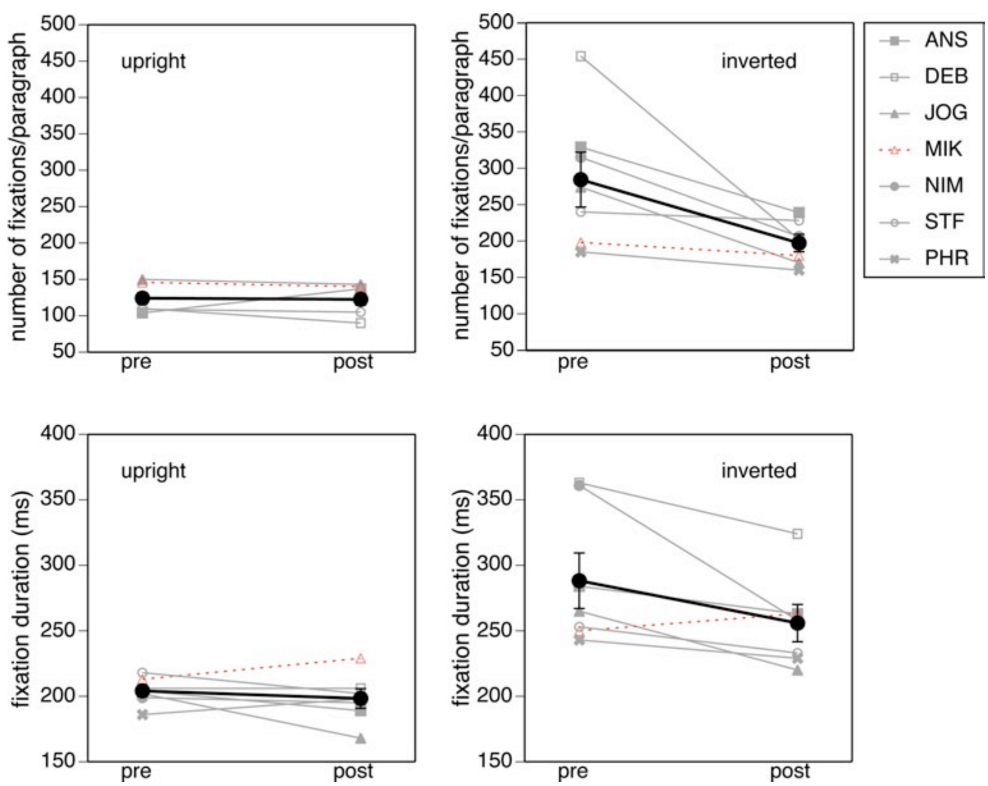

Fig. 6 Paragraph reading, silent. Fixation analysis. Top graphs, fixation number. Bottom graphs, fixation duration. *Left graphs* show performance with upright text and *right graphs* show performance with inverted text. Data for both individual subjects (*gray lines* and *symbols*) and the group mean (*thick black line* and *disk symbol*, with *error bars* showing one standard error) are shown. MIK (*dotted line* and *hollow triangle symbols*) is the subject who did not show improvement in training progression

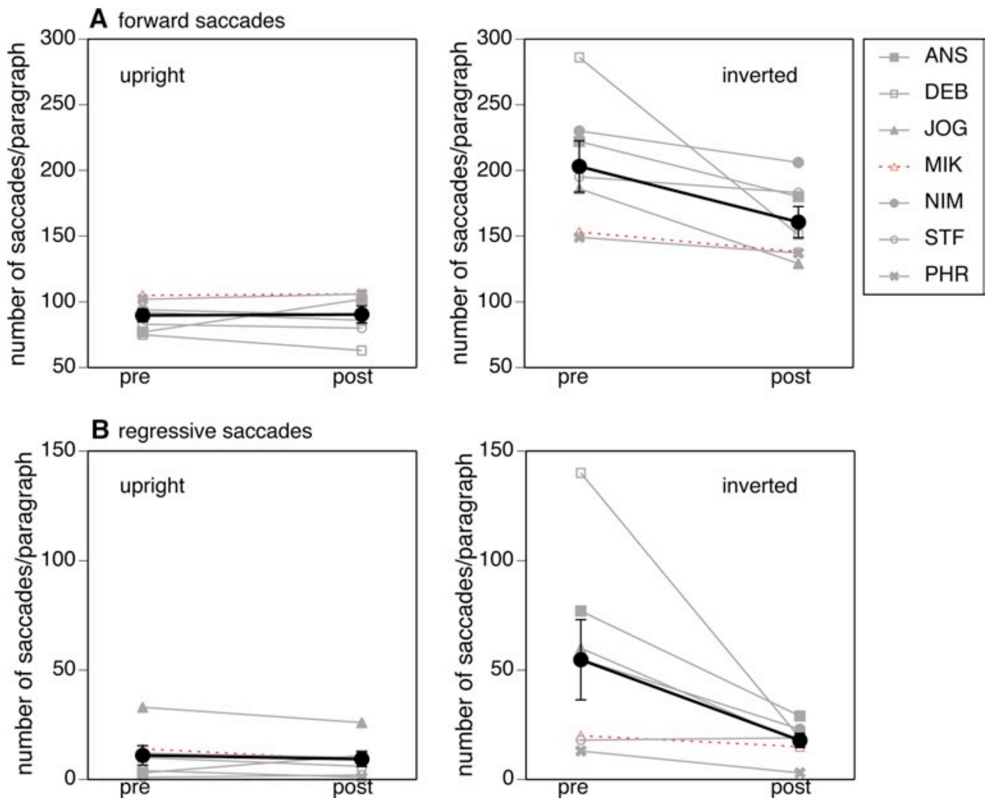

Fig. 7 Paragraph reading, silent. Saccade number analysis. *Top graphs* show number of forward saccades, *bottom graphs* show number of regressive saccades. *Left graphs* show performance with upright text, and *right graphs* show performance with inverted text. Data for both individual subjects (*gray lines* and *symbols*) and the group mean (*thick black line* and *disk symbol*, with *error bars* showing one standard error) are shown. MIK (*dotted line* and *hollow triangle symbols*) is the subject who did not show improvement in training progression

movements used during reading. Our results showed changes in fixation duration and number, the proportion of regressive saccades, and the number and amplitude of forward saccades. In models of reading, fixation duration reflects a decision about when to make the next saccade, which is determined at least in part by the lexical processing occurring during that fixation, since information is acquired only during fixations and not during saccades (Ishida and Ikeda 1989). In the E-Z Reader model (Reichle et al. 2003), for example, completion of a first stage of lexical access or 'familiarity check' is the cue to begin programming a saccade to the next word, while in the SWIFT model (Laubrock et al. 2006), an autonomous process of saccade generation is delayed by lexical processing when word identification is difficult. Hence, fixation durations will be prolonged if word processing is difficult. While the E-Z reader model has usually modeled processing difficulty in terms of linguistic properties such as the frequency and predictability of the word (Reichle et al. 2003), our results show that effects on fixation duration can be generated by perceptual properties such as the orientation of the text. When text is inverted, inefficient perceptual word processing, as manifest by longer response times and increased word-length effects, results in a delay in programming the next saccade, leading to longer fixation durations.

The number of regressive saccades also differed between inverted and upright text. The upright reading saccades of our subjects contained 10 % regressions, consistent with quoted figures of 10–15 % in the literature (Rayner 1998; Reichle et al. 2003), which doubled when text was inverted. The cause of regressive movements is not entirely clear (Rayner 1998; Reichle et al. 2003). They may stem from both ocular motor errors as well as problems processing text, as with syntactically complex passages (Frazier and Rayner 1982). Our study shows that not only linguistic complexity but also perceptual unfamiliarity increases the frequency of regressive saccades.

A larger number of forward saccades may be a secondary effect of both increased number of regressive saccades and reduced amplitude of forward saccades. The latter reflects a decision about where to place the next fixation, which appears to be determined mainly by low-level visual cues such as word length and spacing in parafoveal preview

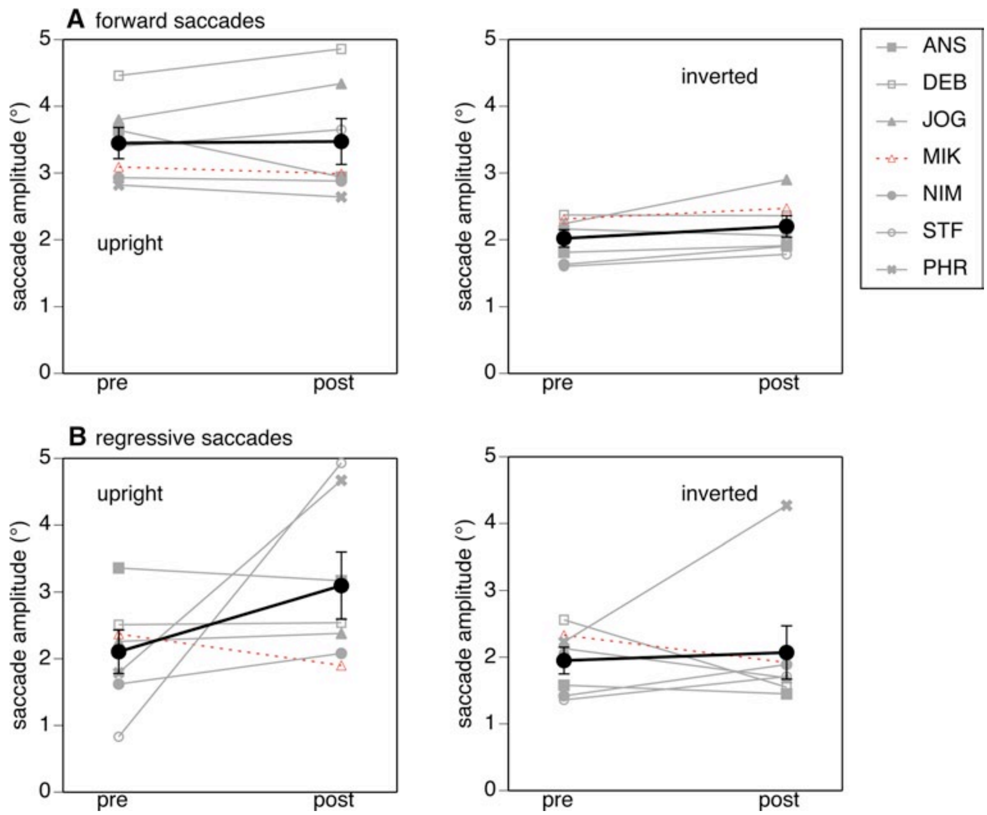

Fig. 8 Paragraph reading, silent. Saccade amplitude analysis. *Top graphs* show amplitudes of forward saccades, and *bottom graphs* show amplitudes of regressive saccades. *Left graphs* show performance with upright text, and *right graphs* show performance with inverted text. Data for both individual subjects (*gray lines* and *symbols*) and the group mean (*thick black line* and *disk symbol*, with *error bars* showing one standard error) are shown. MIK (*dotted line* and *hollow triangle symbols*) is the subject who did not show improvement in training progression

(Reichle et al. 2003). These would not change between upright and inverted text. Our results suggest that additional perceptual factors related to word processing affect saccadic amplitude. Indeed, parafoveal processing can show lexical influences that influence saccadic planning: for example, fixations skip content words (e.g.. nouns, verbs) only 15 % of the time but function words (e.g., 'and,' 'the') 65 % of the time (Rayner and Duffy 1988), and skipping is more likely with predictable words (Rayner et al. 2001). Furthermore, short saccades that re-fixate the same word may be more likely with difficult lexical processing.

Our study showed that many of the deleterious effects of inversion upon reading and its eye movements can be reduced through practice. The impact of inverted reading training on ocular motor parameters was limited to those for inverted text, not surprisingly as reading of upright text may be nearly optimum in our literate subjects. Training reduced most of the pre-training contrasts between upright and inverted text: Hence, after training, subjects made briefer fixations, fewer fixations, and fewer forward and regressive saccades when reading inverted text. Shorter fixation durations suggest more efficient lexical processing during fixations, which is supported by more rapid reading of single words and a smaller word-length effect. More effective word processing may also serve to reduce the number of regressive saccades, though reduced ocular motor error may also contribute to the latter. Interestingly, the amplitude of forward saccades did not change significantly. The reasons for this are not clear, but could include limited improvement in parafoveal processing or minimal expansion of perceptual span. This will require replication and further exploration.

A number of studies have shown that training improves the reading of text in unfamiliar transforms, though most used much shorter periods of learning. Reading of text in a variety of transforms including inversion showed gradually improvement over 4–8 days (Kolers and Perkins 1975), interestingly with variable partial transfer between trained and untrained transforms. In another study, healthy subjects improved their reading times for mirror text over 15 training blocks given over 3 days and retained this skill 3 months later (Cohen and Squire 1980). The neural basis of training on mirror reading was studied by a functional magnetic resonance imaging study, which found that several hours of training with vertically reflected text resulted in decreased activation in parietal cortex and frontal eye fields (Kassubek et al. 2000). Most relevant to our work is a study of 8 students who read 160 pages of text in daily sessions over 2 months (Kolers 1975). This found that inverted reading speed improved from an average of eight times that of upright reading at the beginning of training to only 1.3 times that of upright reading at the end.

Although eye movements were not studied in the above reports, our ocular motor findings for adults learning to read inverted text closely parallel the changes in ocular motor measures as children learn to read upright text. Studies of reading show that over several years of early schooling, fixation duration, the number of fixations, and the proportion of saccades that are regressive decrease, while saccade length increases (Taylor 1965; Lefton et al. 1979; Rayner 1985). Also, a contrast between good and poor readers in the fifth grade showed similar differences, with longer fixation durations, more fixations, and more regressive saccades made by the poor readers (Lefton et al. 1979), suggesting that poor readers fail to make normal developmental gains in ocular motor parameters of efficient reading (Rayner 1998). However, studies of reading development in children and poor readers confound gains in perceptual expertise and improvement of linguistic competency, whereas our study of literate adults reading inverted text isolates the impact of perceptual expertise. One might speculate that the fact that those studies of children showed gains in saccadic amplitude that we did not find implies that amplitude gains are due to gains in linguistic efficiency; however, such an inference is premature. Studies of reading development in children contrast performance in larger cohorts over years, whereas we have studied a small number of subjects training for 10 weeks. Hence, we cannot exclude the possibility that we would find similar gains in saccadic amplitude in a larger group trained for a year or more.

On a practical level, our results are encouraging for the application of this technique to the rehabilitation of right-hemianopic dyslexia. When hemifield loss involves the central 5°, 92 % of patients with right hemianopia complain of reading difficulties despite otherwise intact language skills (Schuett et al. 2008b). This 'hemianopic dyslexia' ranks as one of the most important functional impairments following brain injury on occupational and daily life quality (Papageorgiou et al. 2007; Schuett et al. 2008b). Because we read from left to right, patients with right hemianopia have severely truncated visual and perceptual spans and lack the parafoveal preview of upcoming segments (Kerkhoff et al. 1992). The net result is slow reading with abnormal ocular motor parameters (Schuett et al. 2008b), including a large number of fixations, longer durations of fixations, and saccades of smaller amplitude (McDonald et al. 2006). Rehabilitation of reading in right hemianopia has focused primarily on methods to increase the amplitude of rightward saccades during reading, which has results in some gains in reading speed (Spitzyna et al. 2007; Schuett et al. 2008a). However, the gains from these approaches may ultimately be limited by the fact that they cannot restore visual span and perceptual span to the right of fixation. By turning text upside-down, the reading direction is reversed. Since the asymmetries in visual and perceptual span are reversed in subjects who read languages from right to left, such as Hebrew and Farsi (Pollatsek et al. 1981), these properties are plastic and dependent on experience: Hence, practice with inverted reading has the potential to restore the processing of upcoming text when this is now placed in the left hemifield. The downside of the inverted reading approach is that it requires subjects to develop a new perceptual expertise for an unfamiliar orientation, but our study of healthy subjects shows that this expertise can be acquired at least partially through training. If one extrapolates linearly from our results, one might anticipate that extending training to 30–50 weeks may result in inverted reading performance equivalent to upright reading. The assumption of linearity, however, is a significant one: Indeed, one might reasonably predict an eventual decline in the rate of gain with further practice. Given the years of reading experience of literate adults, it may be unrealistic to expect that proficiency with inverted text can approach that with upright text after only several months of training. Nevertheless, substantial improvements in inverted reading may still be of considerable benefit to patients with right-hemianopic dyslexia, even if they fall short of upright equivalency.

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